

## **Overview of Small and Large-Scale Space Solar Power Concepts**

**Seth Potter and Mark Henley**  
**The Boeing Company**  
**Huntington Beach, CA**

**Joe Howell, Connie Carrington, and  
John Fikes**  
**NASA Marshall Space Flight Center**  
**Huntsville, AL**

### **Abstract for the International Space Development Conference and Sunsat Energy Council Meeting Los Angeles, CA, 3-7 May 2006**

An overview of space solar power studies performed at the Boeing Company under contract with NASA will be presented. The major concepts to be presented are:

1. **Power Plug in Orbit:** this is a spacecraft that collects solar energy and distributes it to users in space using directed radio frequency or optical energy. Our concept uses solar arrays having the same dimensions as ISS arrays, but are assumed to be more efficient. If radiofrequency wavelengths are used, it will necessitate that the receiving satellite be equipped with a rectifying antenna (rectenna). For optical wavelengths, the solar arrays on the receiving satellite will collect the power.
2. **Mars Clipper / Power Explorer:** this is a solar electric Mars transfer vehicle to support human missions. A near-term precursor could be a high-power radar mapping spacecraft with self-transport capability. Advanced solar electric power systems and electric propulsion technology constitute viable elements for conducting human Mars missions that are roughly comparable in performance to similar missions utilizing alternative high thrust systems, with the one exception being their inability to achieve short Earth-Mars trip times.
3. **Alternative Architectures:** this task involves investigating alternatives to the traditional solar power satellite (SPS) to supply commercial power from space for use on Earth. Four concepts were studied: two using photovoltaic power generation, and two using solar dynamic power generation, with microwave and laser power transmission alternatives considered for each. All four architectures use geostationary orbit.
4. **Cryogenic Propellant Depot in Earth Orbit:** this concept uses large solar arrays (producing perhaps 600 kW) to electrolyze water launched from Earth, liquefy the resulting hydrogen and oxygen gases, and store them until needed by spacecraft.
5. **Beam-Powered Lunar Polar Rover:** a lunar rover powered by a microwave or laser beam can explore permanently shadowed craters near the lunar poles to search for water ice and other frozen volatiles. Near such craters are mountain peaks and highlands that are in near permanent sunlight. Power can be beamed from a collector on a sunlit mountain or crater rim to a rover inside a crater.

Near-term applications of space solar power technology can therefore pave the way toward large-scale commercial power from space.

# Overview of Small & Large-Scale Space Solar Power Concepts

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Seth Potter & Mark Henley  
The Boeing Company  
5301 Bolsa Avenue, MC H013-C321  
Huntington Beach, CA 92647  
Telephone: (714) 372-2941  
E-mail: [seth.d.potter@boeing.com](mailto:seth.d.potter@boeing.com)

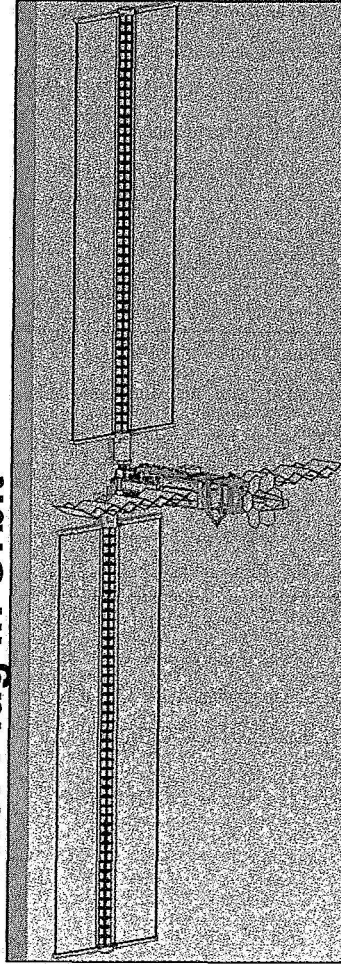


Joe Howell, Connie Carrington, & John Fikes  
NASA Marshall Space Flight Center  
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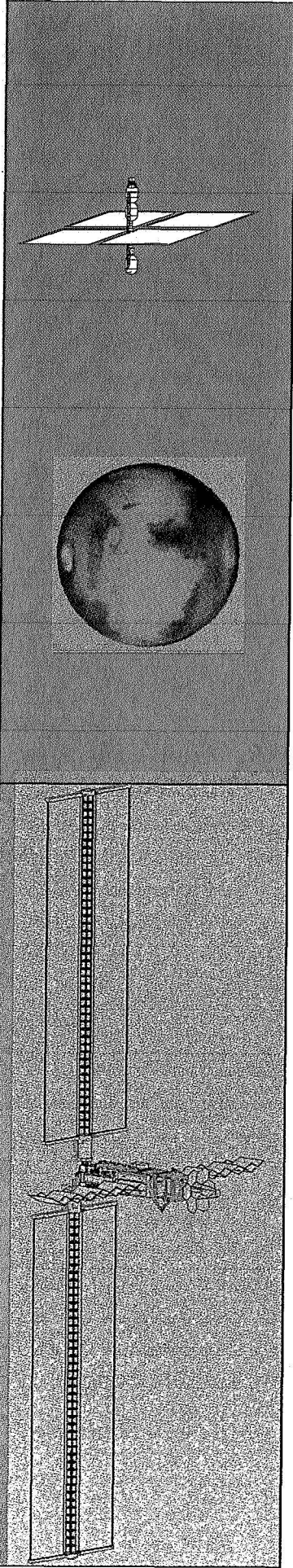


# Boeing Has Studied Several Space Solar Power-Related Concepts

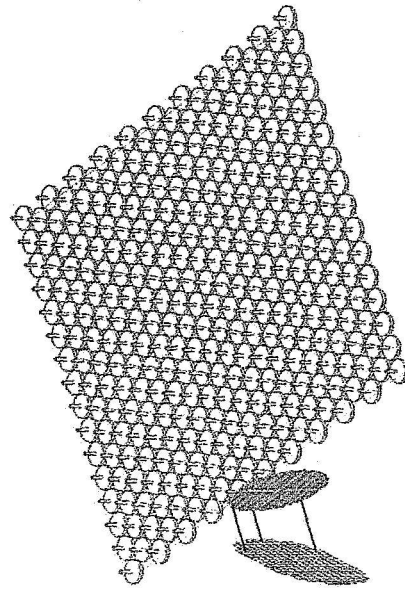
Power Plug in Orbit



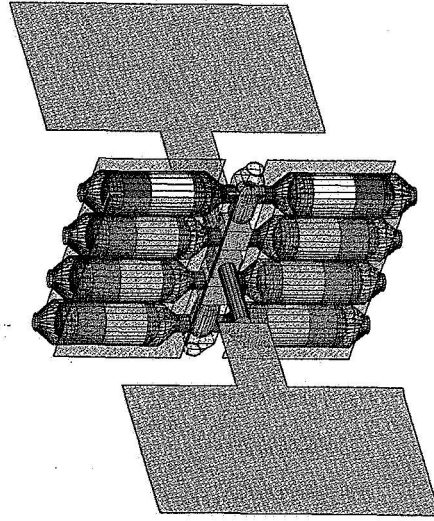
Mars Clipper



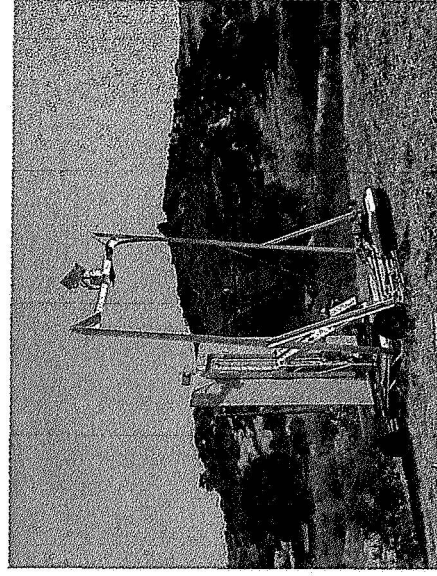
Alternative SPS Architectures



Cryogenic Propellant Depot



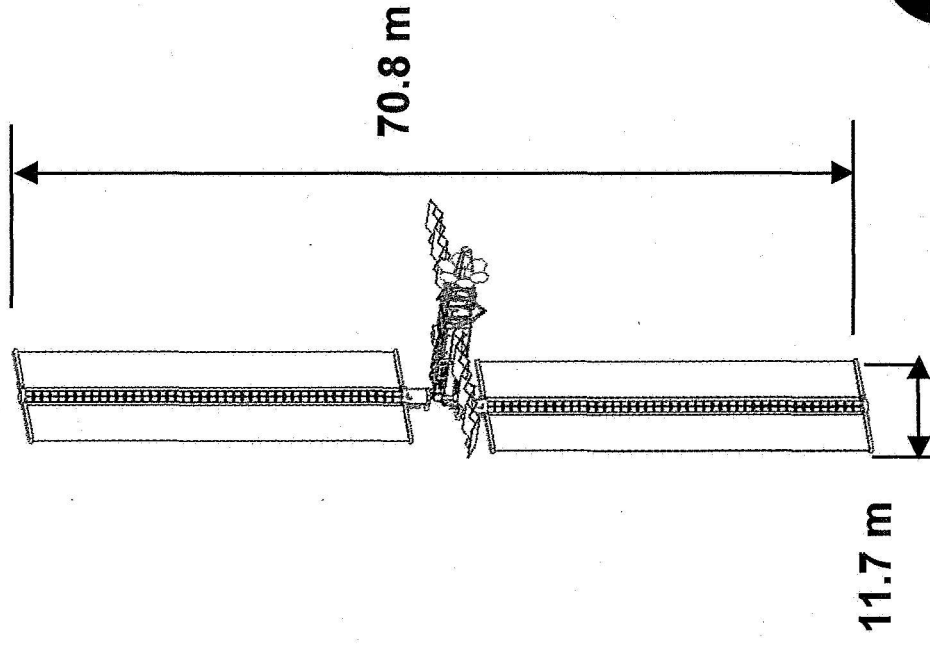
Beam-Powered Lunar Rover



# Power Plug (Space-to-Space Power Beamer)

- Demonstrates deployment of space solar power modules
- Demonstrates solar electric propulsion
- Demonstrates solar-powered wireless power transmission
  - Efficient power generation
  - Efficient power transmission
  - Effective heat dissipation
  - Accurate pointing of beam
  - Use ISS-compatible arrays; current ISS array pair produces 61.5 kW
    - > Advanced cells may increase this to ~120 kW
    - > For 30% power conversion efficiency, this yields ~36 kW in beam
- Mass: approximately 20 metric tonnes

Array dimensions are similar to ISS

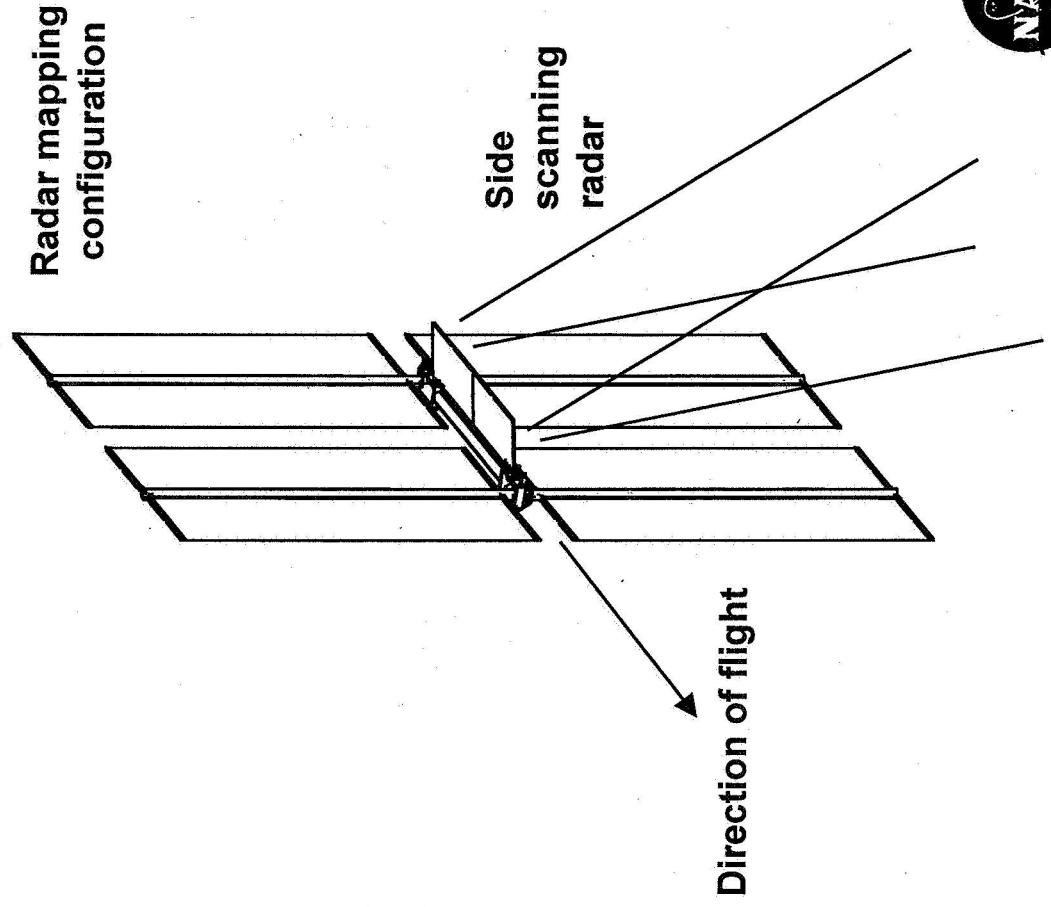


## Power Plug: Additional Applications

- Power Plug can be a spacecraft bus carrying a payload which can be:
  - Wireless power transmission system
  - Communications package
  - Science or exploration payload
- Missions and demonstrations can include:
  - Wireless power transmission (WPT) demonstrations
    - > Space to space
    - > Space to planetary surface
  - Other advanced technology demonstrations
    - > Advanced solar cells
    - > Solar electric propulsion
  - High power communications satellite
  - Solar electric transfer of WPT, scientific, or communications package from LEO to:
    - > MEO
    - > GEO
    - > Moon

# “Power Explorer” Radar Mapping Spacecraft

- Approach: Design spacecraft based on two half-size segments of SSP Sun Tower
- Dimensions: Two pairs 52 m x 31 m solar panels (four panels total) with 32 m x 8 m transmitter/receiver (assembled from two 16 m x 8 m panels)
- Power source: onboard solar cells power a 5.8 GHz radar beam and Hall Effect Thrusters at a peak total power level of ~4 MW near Earth



# Mars Clipper Solar Electric Vehicle

Human Mars missions can consist of 3 vehicles:

- **Cargo 1 Transfer Stage: Unpiloted Lander**, consisting of

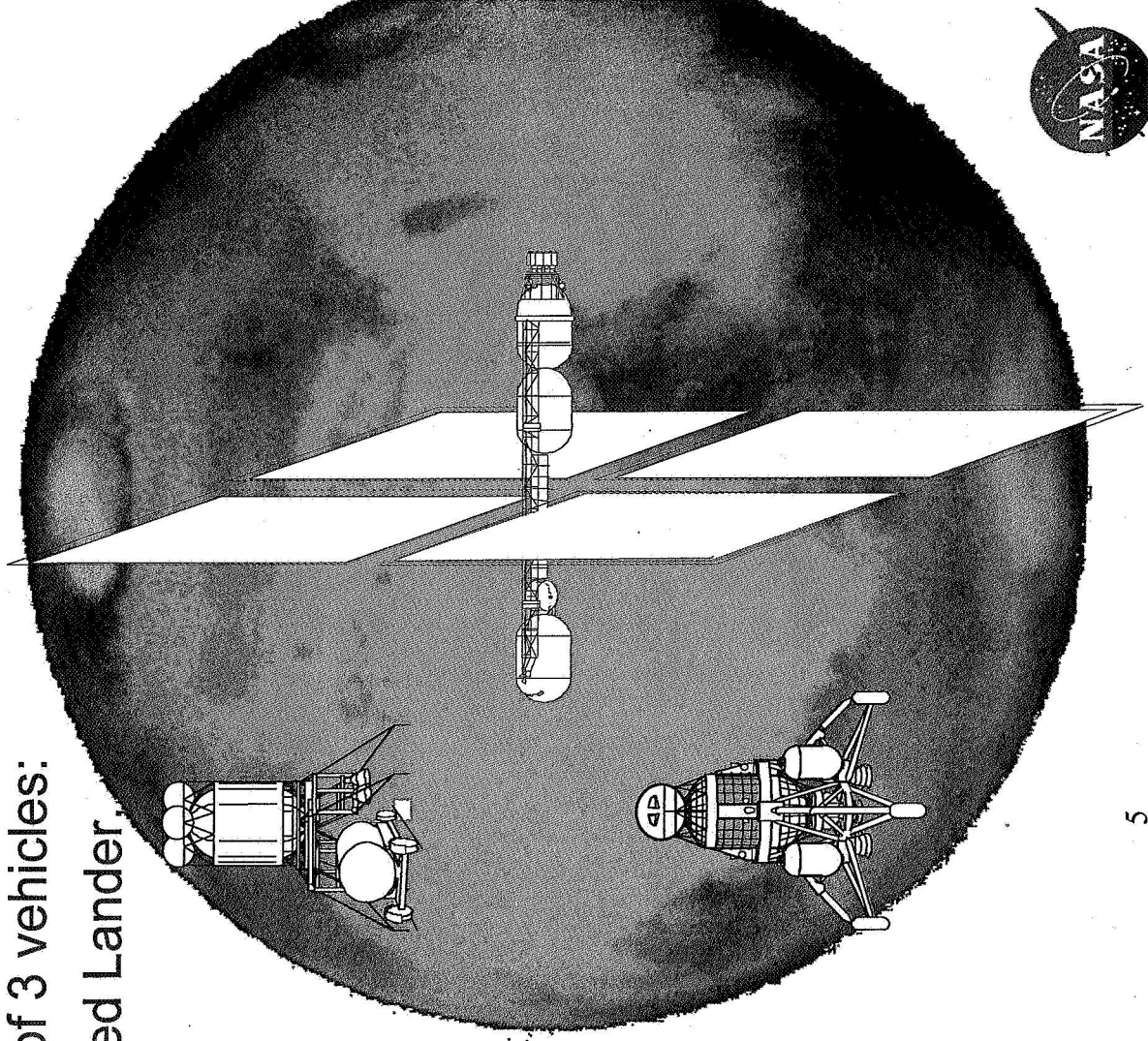
- Surface habitat
- Equipment
- Surface rover
- Consumables
- Aeroshell: not shown in illustration
- 57371 kg total mass

- **Cargo 2 Transfer Stage: Piloted Ascent/Descent Stage**

- Aeroshell: not shown in illustration
- 57,771 kg total mass

- **Piloted Transfer Stage**

- 268 MT IMLEO for expendable
- 501 MT IMLEO for reusable



# Mars Clipper Piloted Mission Parameters

Phase	Initial Orbit (km)	Final Orbit (km)	Mass			Time (days)	Tot Mission Duration (days)	Delta-V (km/s)
			Initial (mt)	Propel (mt)	Final (mt)			
LEO to Earth Escape	300 x 300	E Escape	501	153	347	267	267	7.15
Earth Escape to Mars Orbit Capture	E Escape	250 x 33,000 Mars	347	114	232	255	522	8.16
Mars Surface Stay	—	—	232	0	232	600	1122	0
Mars Capture Orbit to Matching Earth Vel	250 x 33,000 Mars	E Escape	232	71	160	156	1278	8.16
Matching Earth Arrival Vel to Earth LEO	E Escape	300 x 300	160	42	118	74	1352	7.15

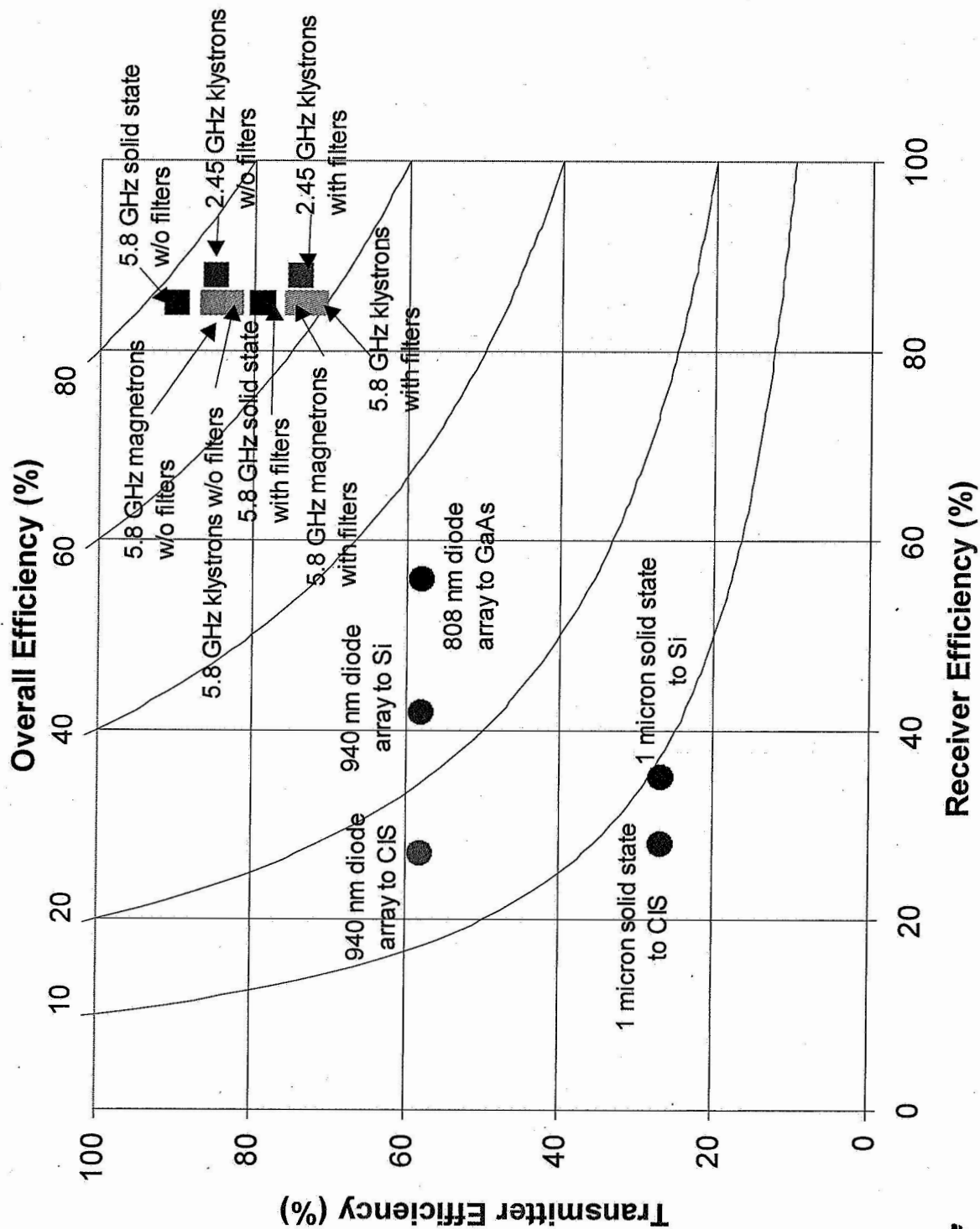
# WPT Frequency Trade for SSP Alternative Architectures

ATTRIBUTE	MICROWAVES	OPTICAL WAVELENGTHS
Aperture Size	Large, so system must be large	Small; gives flexibility of system design
Interference	Electromagnetic spectrum	None, except perhaps astronomy
Rain, Cloud Attenuation	Lower frequencies can penetrate clear air, clouds, and light rain	Optical wavelengths are attenuated by clouds and rain
Legal Issues	FCC, NTIA, ITU	ABM treaty, if power density high
Dual Use of Infrastructure	Rectennas used for SSP only (possibly communication)	Terrestrial PV arrays can receive sunlight
Dual Use of Land	Crops or PV under rectennas	PV arrays on rooftops, etc.
Perception Issues	Public fears of "cooking"	Governments may fear weapons application
Safety	Safe, but must keep aircraft out of beam	Safe, if power density is kept low
Efficiency of space segment	High	Improving
Efficiency of ground segment	High	Improving
Traceability	Heritage to communications and radar	MSC 1 and 3
PMAD	Heavy due to centralized WPT	Light, WPT can be distributed

## Solar Power Satellite Alternative Architectures

- Four options considered; based on power generation and power transmission methods:
  - Photovoltaic power generation, microwave power transmission;
  - Photovoltaic power generation, laser power transmission;
  - Solar dynamic power generation, microwave power transmission;
  - Solar dynamic power generation, laser power transmission.
- All four options use geostationary orbit.

# Wireless Power Transmission Efficiencies

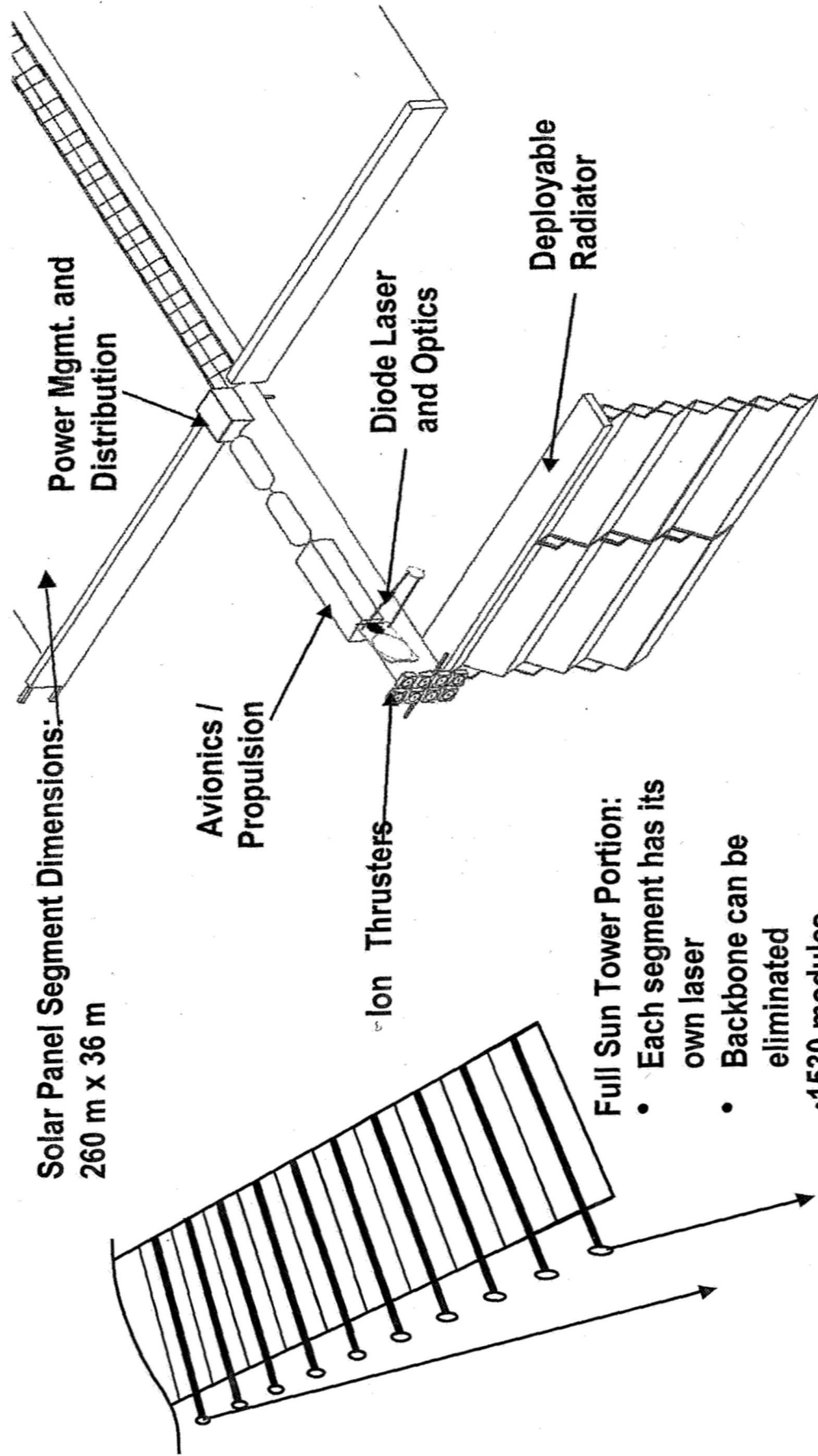


# Photovoltaic / Microwave SPS GEO Sun Tower Concept

- Power transmitted: 3 GW
- Power into terrestrial grid: 1.2 GW
- Solar array "wing span": 500 m
- 355 array pairs
- Total length: 16 km
- Transmitter array is 500 m in diameter
- Power transmission frequency: 5.8 GHz
- Mass: 26,500 metric tonnes (includes LEO-to-GEO self-transport capability)
- Mass: 22,900 metric tonnes (not including self-transport capability)



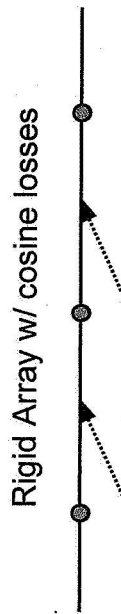
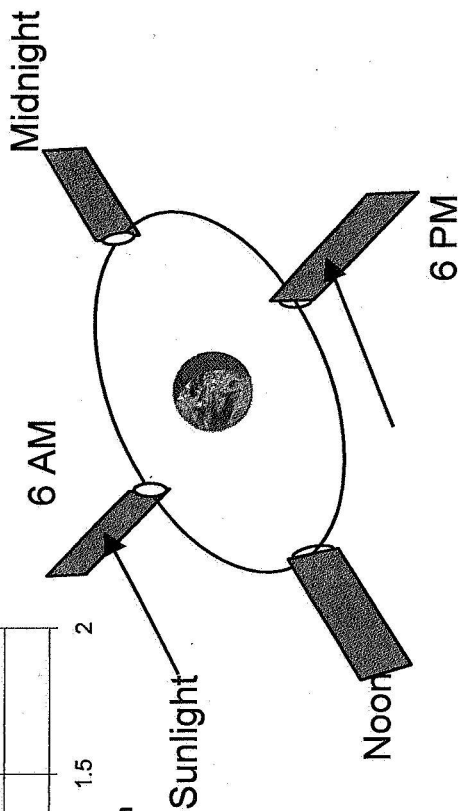
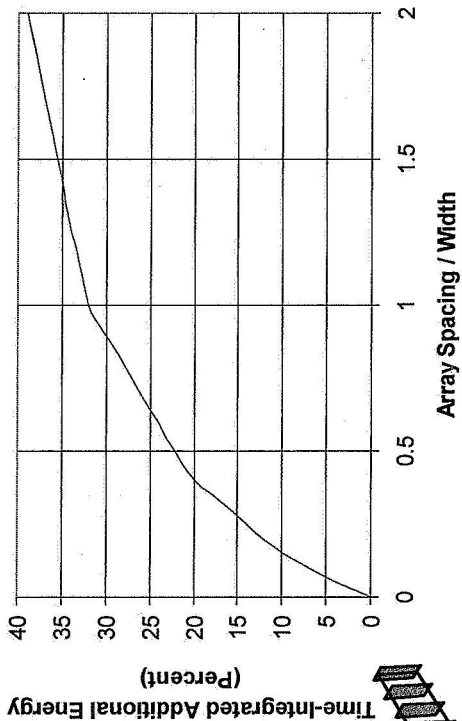
# Photovoltaic Laser SPS Concept



## Laser SPS and Terrestrial PV: Possible Synergy

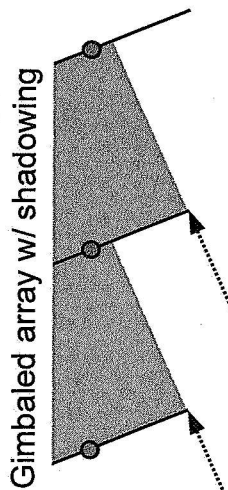
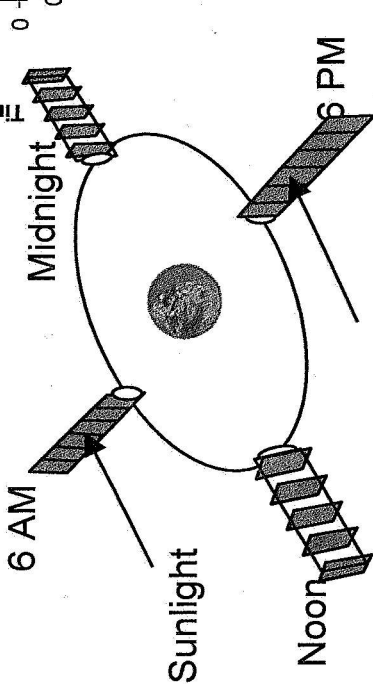
- Large terrestrial photovoltaic power plants may already be in place in desert locations (Mojave, Sahara, Gobi, etc.) by the time SPSs are deployed
- Laser SPS provides an additional source of illumination to these arrays
  - Most promising laser technology has wavelengths that are near bandgap of common PV cells, so SPS illumination is converted more efficiently than sunlight
- Gravity gradient-stabilized SPSs are in peak insolation at ~6 AM and ~6 PM, with shadowing or cosine loss at mid-day and midnight
  - Mass and complexity of gimbaled arrays may add little extra power at these times
  - Both sides of SPS PV arrays can be light-sensitive, but back side may lose ~30% power due to darkening of Kapton substrate
- Laser illumination plus ambient sunlight combine at terrestrial PV array to approximate the daily electricity demand pattern

# Gimbaled vs. Rigid Sun Tower



## Rigid Array

- Cosine losses around noon & midnight cannot be avoided
- Balanced electrical and thermal loads
- Closer packing reduces overall length

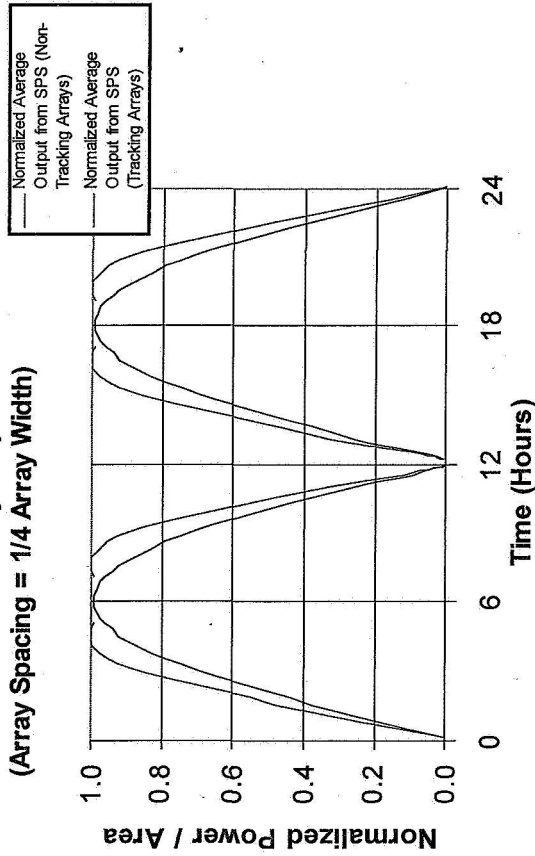


## Gimbaled Array

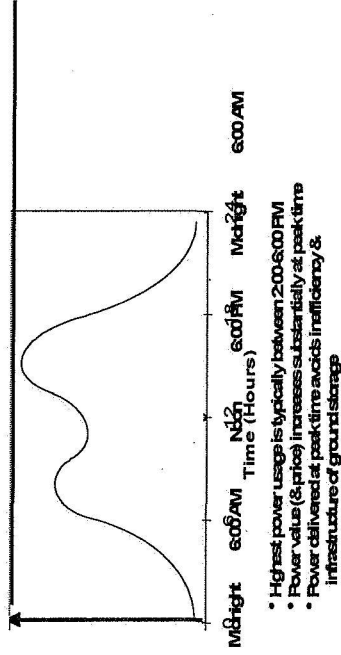
- Gimballing mechanisms avoid cosine losses
- Shadowing losses around noon & midnight cannot be avoided
- Shadowing complicates cell arrangement and PMAD operation

# Power Output of Laser SPS Can Be Combined With Ambient Sunlight to Follow Demand

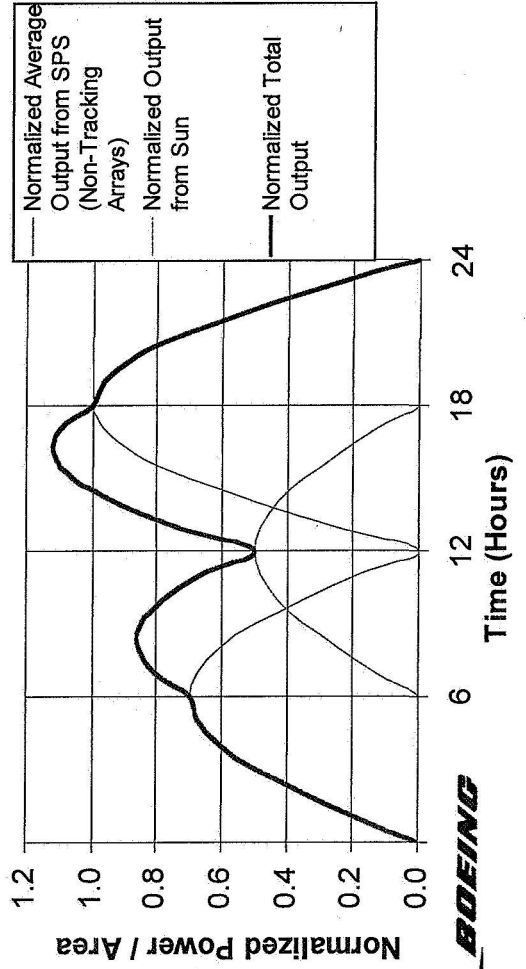
Terrestrial PV Array Output  
(Array Spacing = 1/4 Array Width)



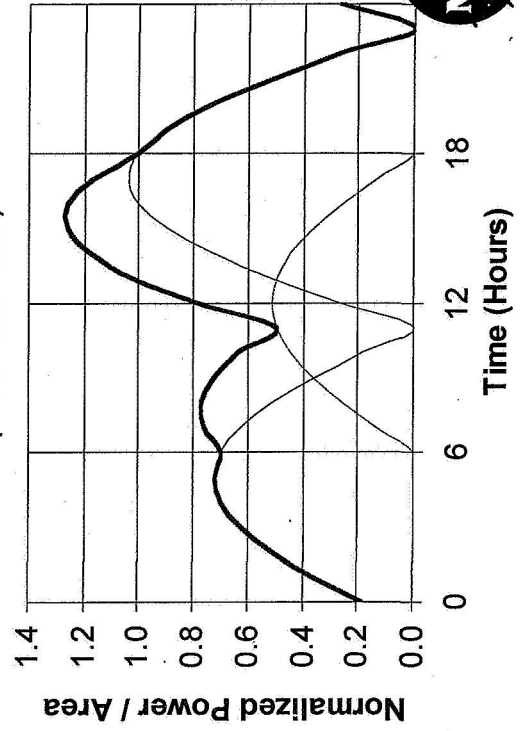
Daily Electricity Demand Pattern



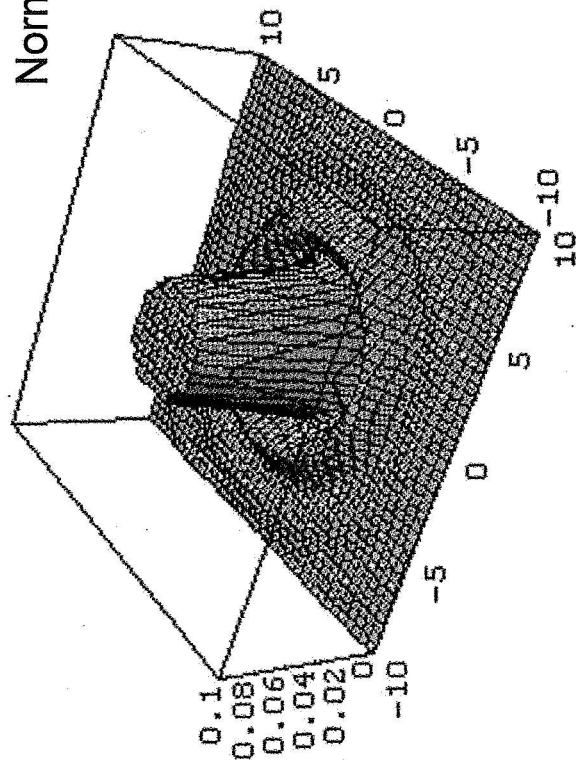
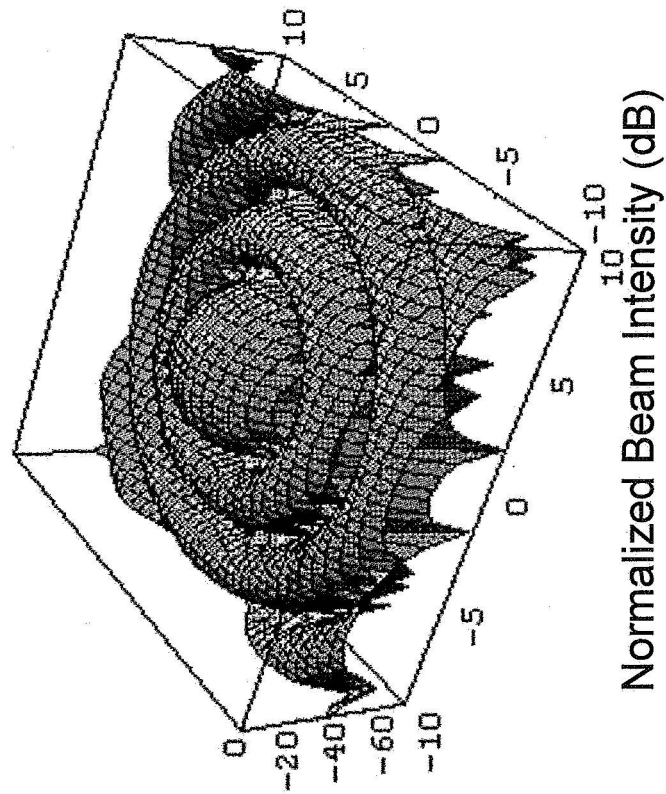
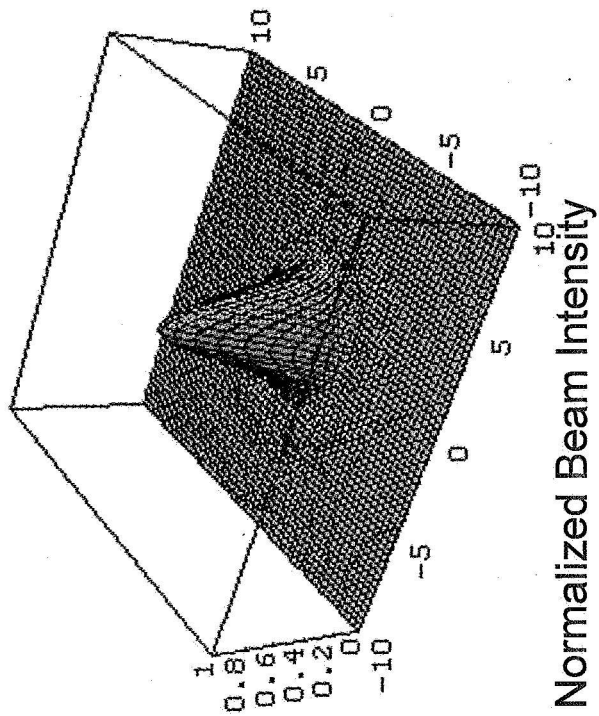
Terrestrial PV Array Output: Sun + SPS Power  
Normalized to Peak Output from SPS w/o Sun



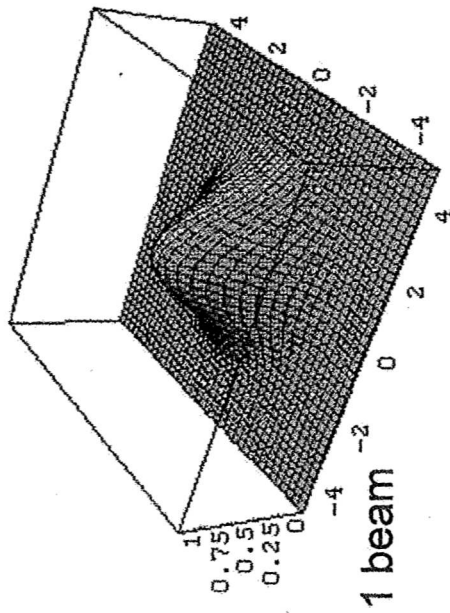
Terrestrial PV Array Output: Sun + SPS Power  
Normalized to Peak Output from SPS w/o Sun  
(1 Hour Time Offset)



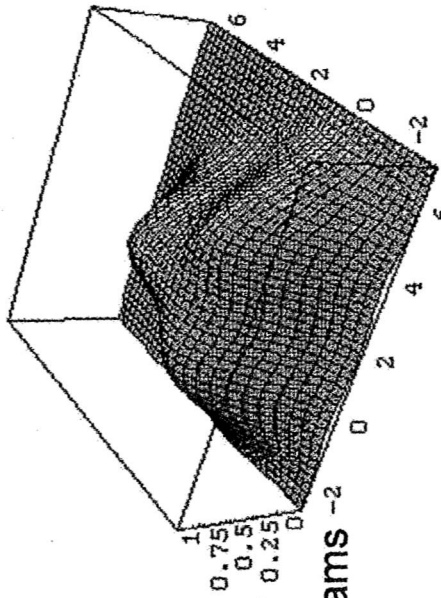
# Diffraction-Limited Beam Intensity from a Uniformly Illuminated Circular Aperture



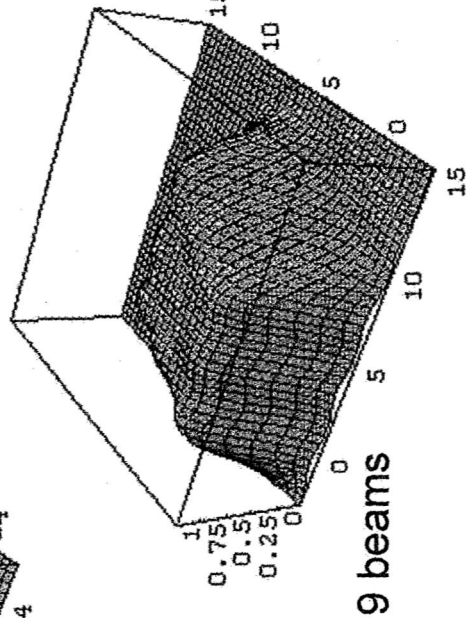
# Building Top-Hat Beam Profile with Overlapping Out-of-Phase Laser Beams



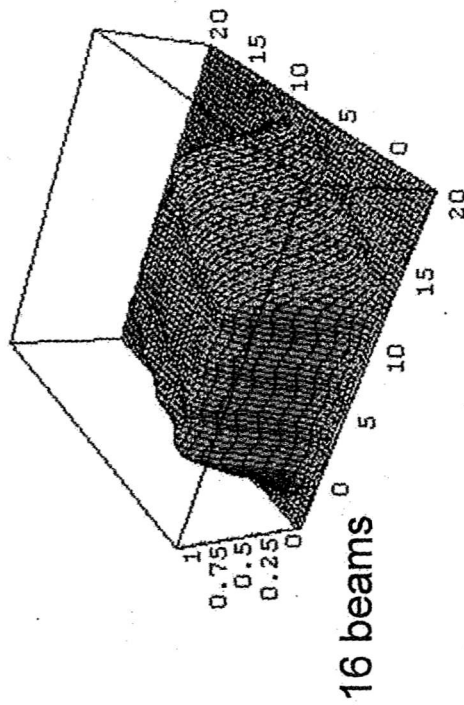
1 beam



3 beams



9 beams



16 beams

## Notes:

- Horizontal scale not held constant in plots.
- Geometric arrangement of multiple beams not necessarily configured to minimize edge effects.
- Diffraction-limited beams assumed.

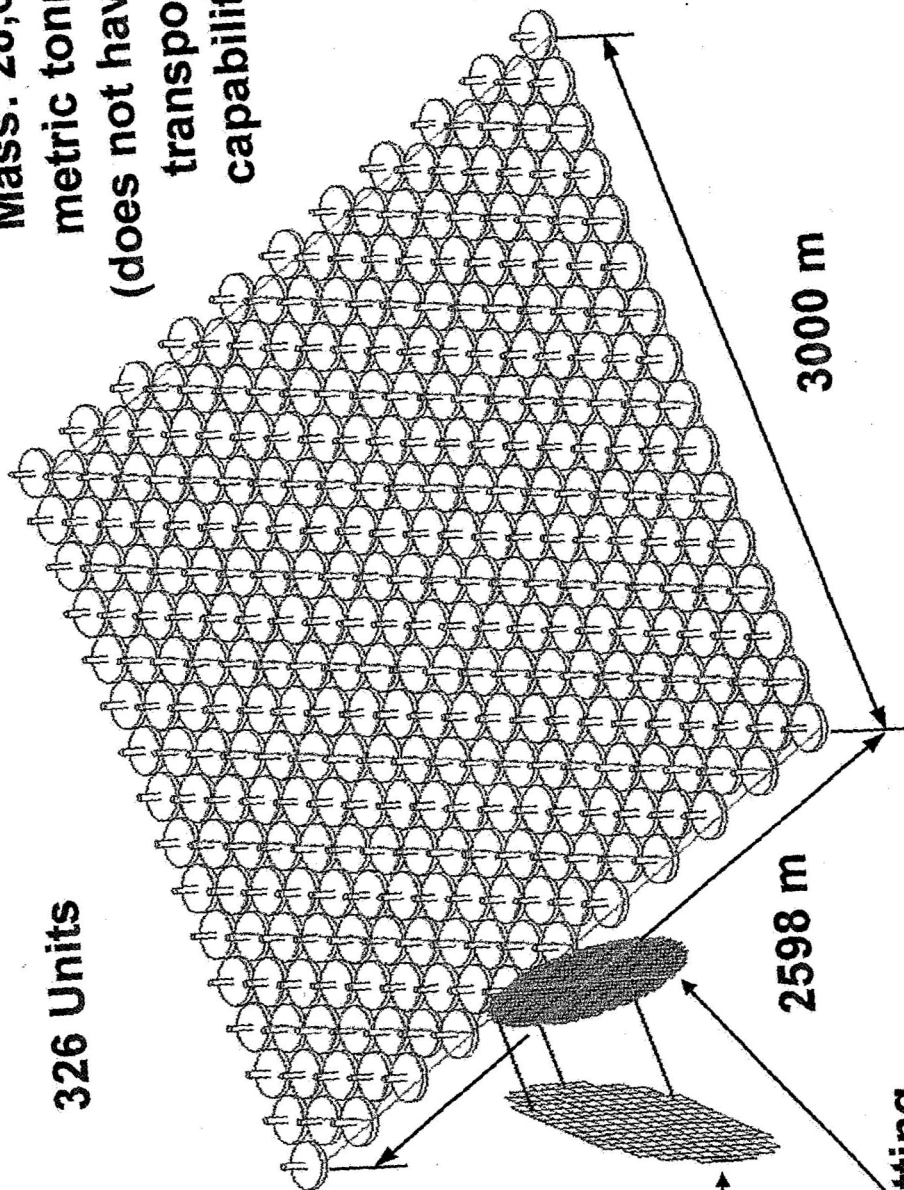
# Power Generation Trade for SPS Alternative Architectures

ATTRIBUTE	PHOTOVOLTAIC	SOLAR DYNAMIC
Solar Collector Area	Moderately high, but improving	Low
Radiation Tolerance	Degrades	Excellent
Specific Power	Moderate	Low, but should be high in far term
Efficiency	~25% SOA with rainbow cells	Currently 29%; expect 35% in far term
Heat Tolerance	Loses efficiency as Temp. rises	Excellent; requires heat
Moving Parts	None	Rotating machinery, fluids
Modular Construction	Yes	Less so
Experience in Space Environment	Extensive use on satellites	Vacuum chamber only

# Solar Dynamic / Microwave SPS GEO Abacus-Like POP Concept

Mass: 28,000  
metric tonnes  
(does not have self-  
transport  
capability)

326 Units

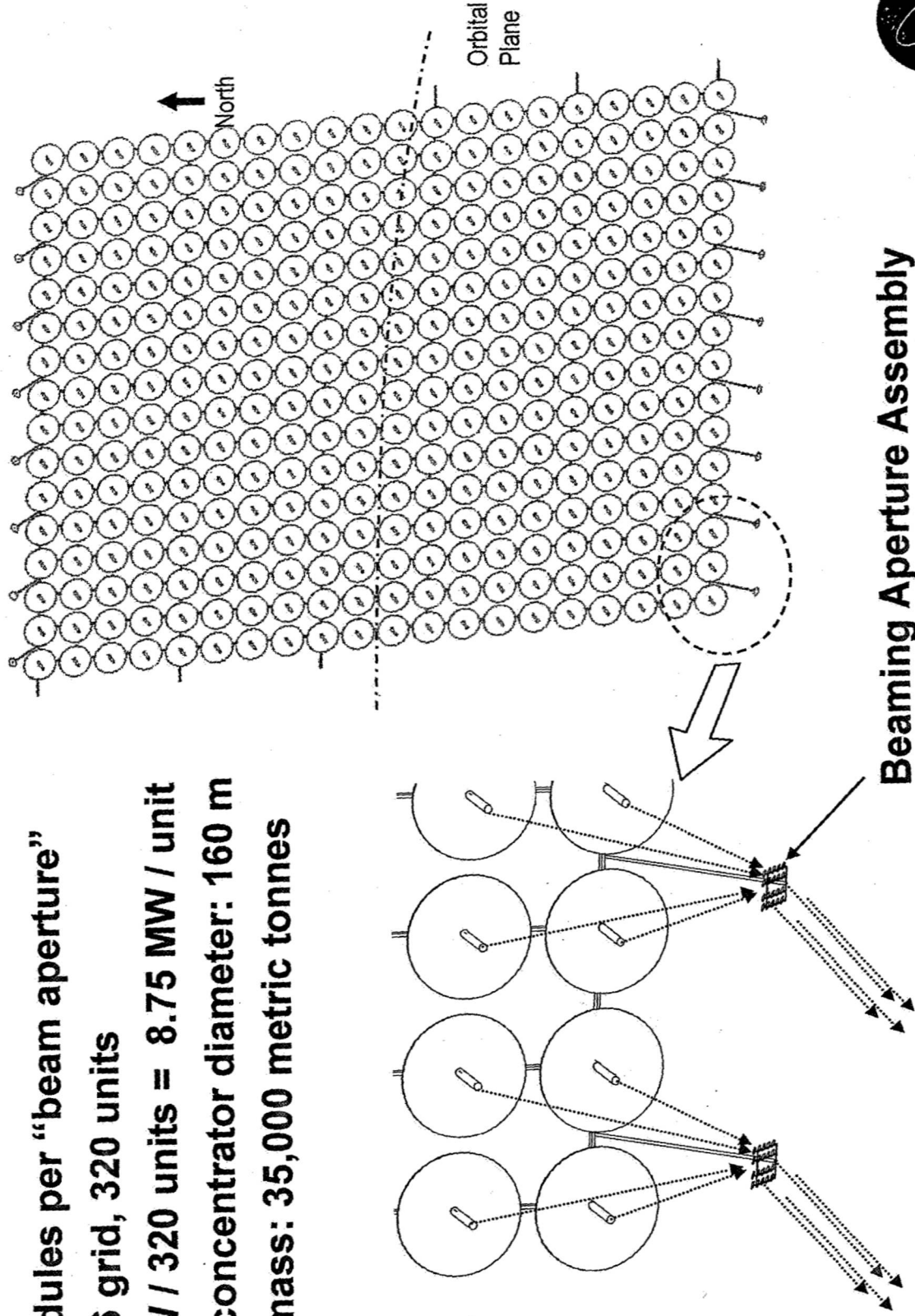


Reflector:  
520 x 690 m

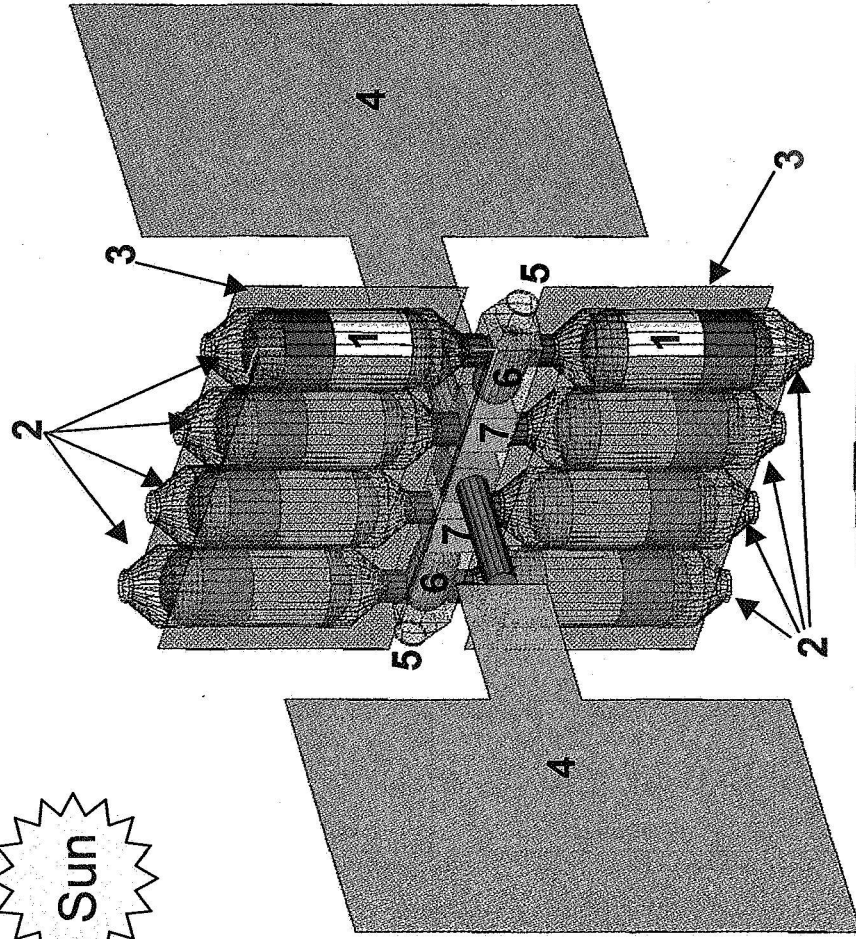
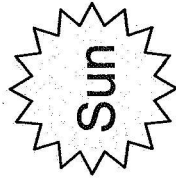
Transmitting  
Antenna: 500 m

# Solar Dynamic / Laser SPS GEO Abacus-Like SPS Concept

- 20 modules per "beam aperture"
- 20 x 16 grid, 320 units
- 2.8 GW / 320 units = 8.75 MW / unit
- Solar concentrator diameter: 160 m
- Total mass: 35,000 metric tonnes



# Propellant Production Depot Design Includes Seven Key Subsystems



1. LOX/LH2 Storage Tanks

2. Transfer Vehicle Docking Ports

3. Radiators

4. Solar Arrays

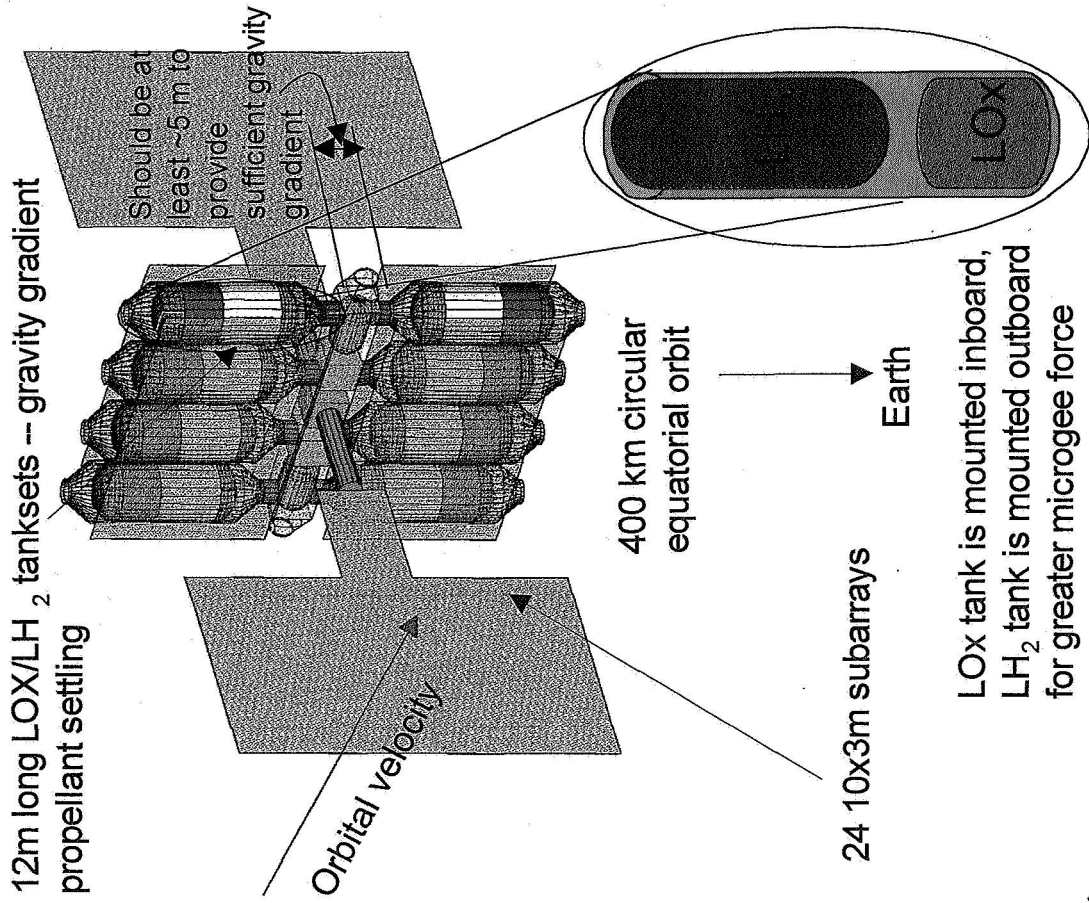
5. Water Docking Port

6. Water Storage Tanks

7. Electrolysis System

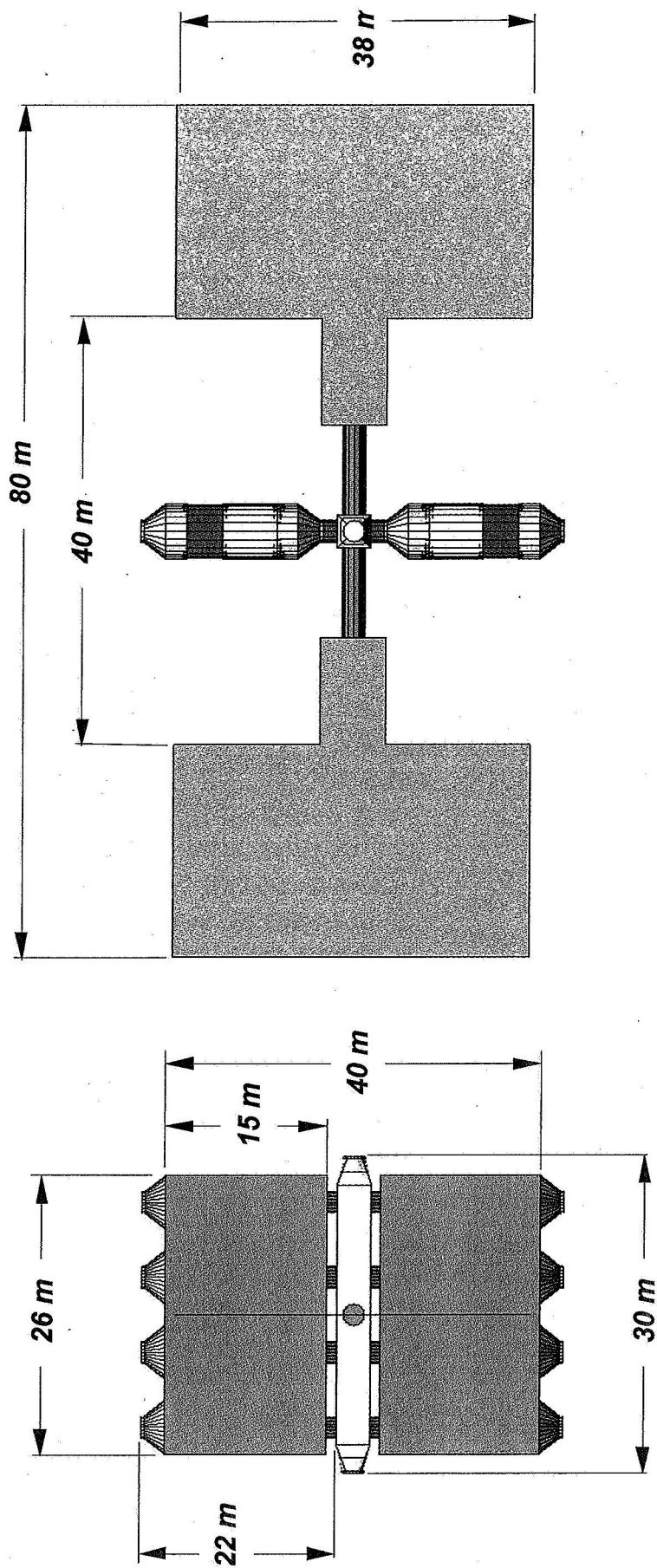


# System Design Features of the Propellant Production Depot



- ENTECH Stretched Lens Array (SLA's)
  - Sized for 706kWe (635kWe delivered to bus)
  - Inflatable abacus structure
- Power Management & Distribution (PMAD)
  - 150V
  - No converters at the arrays
  - Two power conducting slip rings
- 8 Delta IV Heavy-class tanksets
  - 500 MT LOX & LH<sub>2</sub> per year
  - Stoichiometric 8:1 mixture ratio
- Composite truss structure
- Robotics including infrastructure
- Stationkeeping & attitude control
  - SEP 0.5N thrusters
  - 50kWe Hall thrusters
  - CMGs
  - Attitude sensors
  - Krypton stationkeeping propellant for 10 years

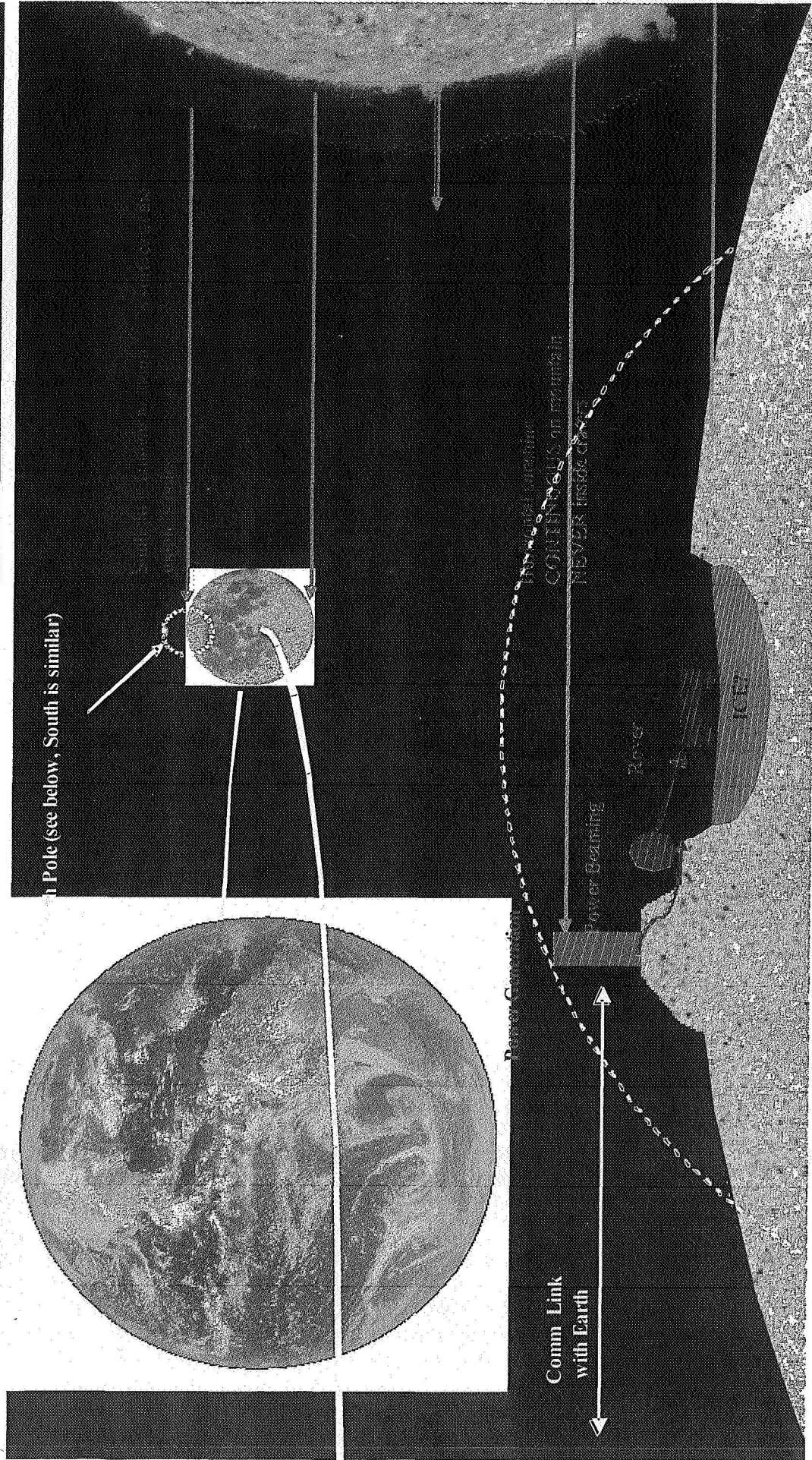
# Propellant Production Depot Configuration Dimensions



## Space Solar Power Technology Demonstration for Lunar Polar Applications

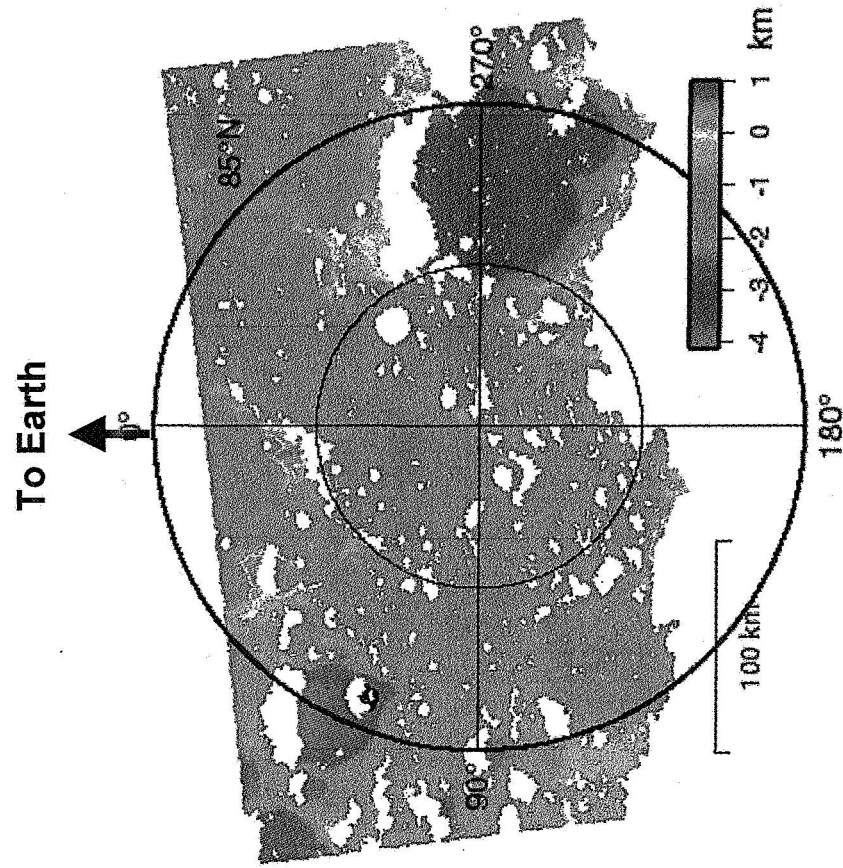
- Technology for Laser-Photo-Voltaic Wireless Power Transmission (Laser-PV WPT) has been developed for lunar polar applications by Boeing and NASA Marshall Space Flight Center
- A lunar polar mission could demonstrate and validate laser-photovoltaic wireless power transmission and other SSP technologies, while enabling access to cold, permanently shadowed craters that are believed to contain ice
  - Craters may hold frozen water and other volatiles deposited over billions of years, recording prior impact events on the moon (and Earth)
  - A photovoltaic-powered rover could use sunlight, when available, and laser light, when required, to explore a wide range of lunar polar terrain.

# General Concept for Initial Lunar Polar Space Solar Power System

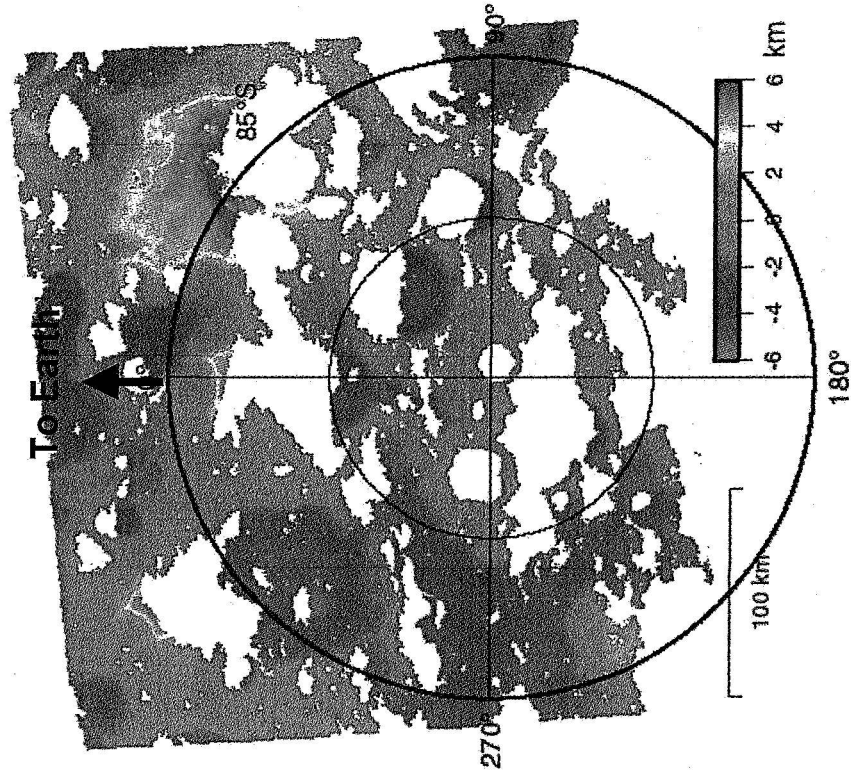


# Radar-Derived Topography of the Moon's North and South Poles

- Note Difference in Vertical Scale!!!



North Pole > 85 degrees

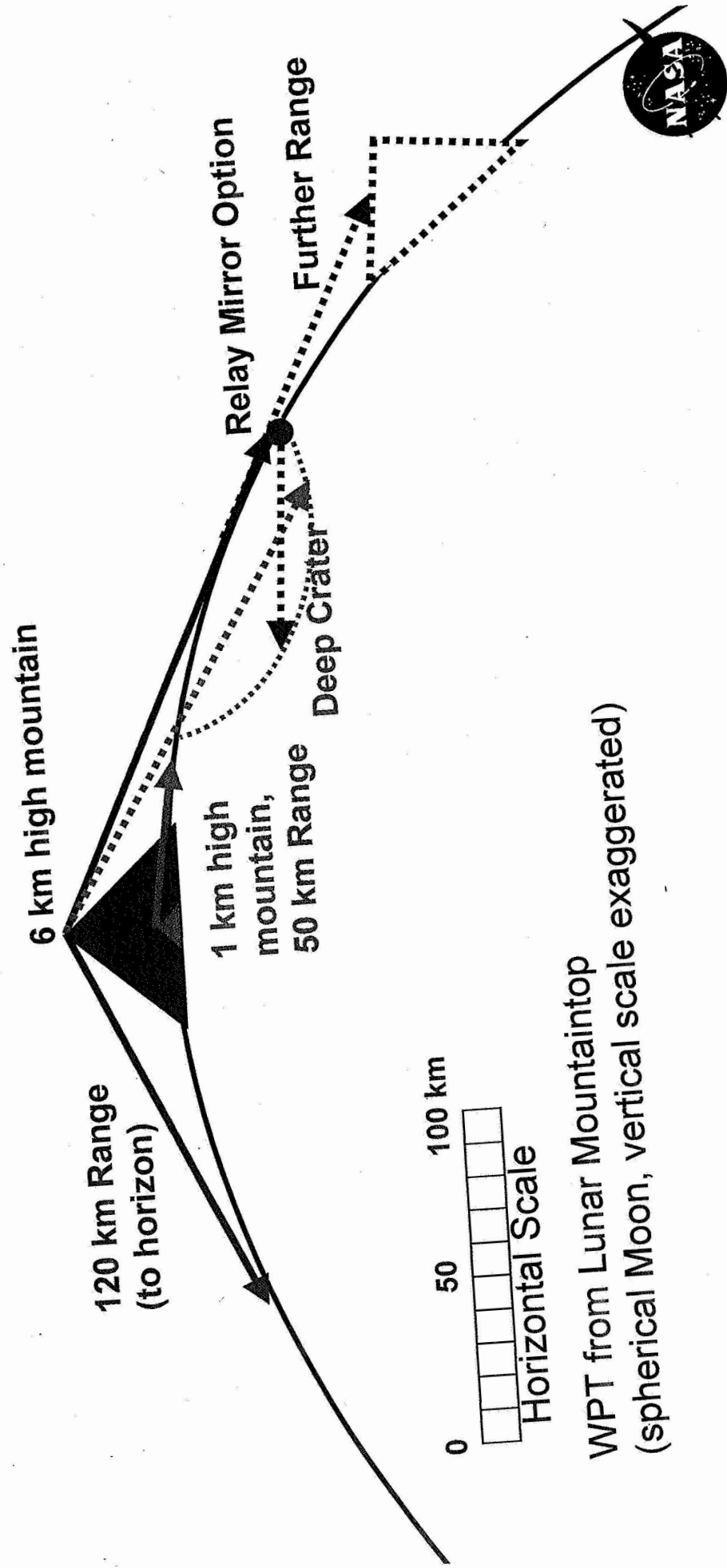


South Pole > 85 degrees



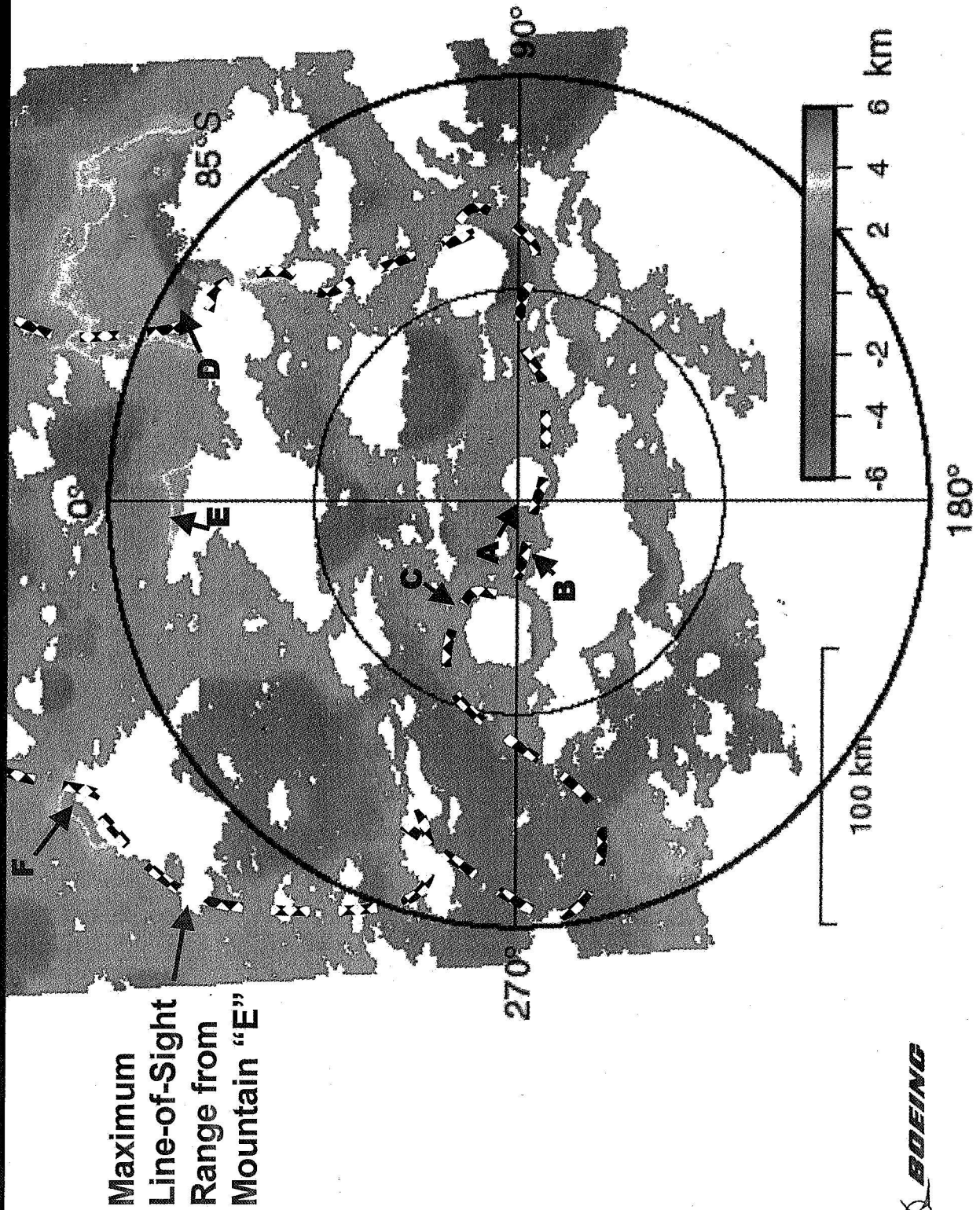
# Laser Range Depends on Topography

Transmitter on lunar mountain could beam power > 100 km

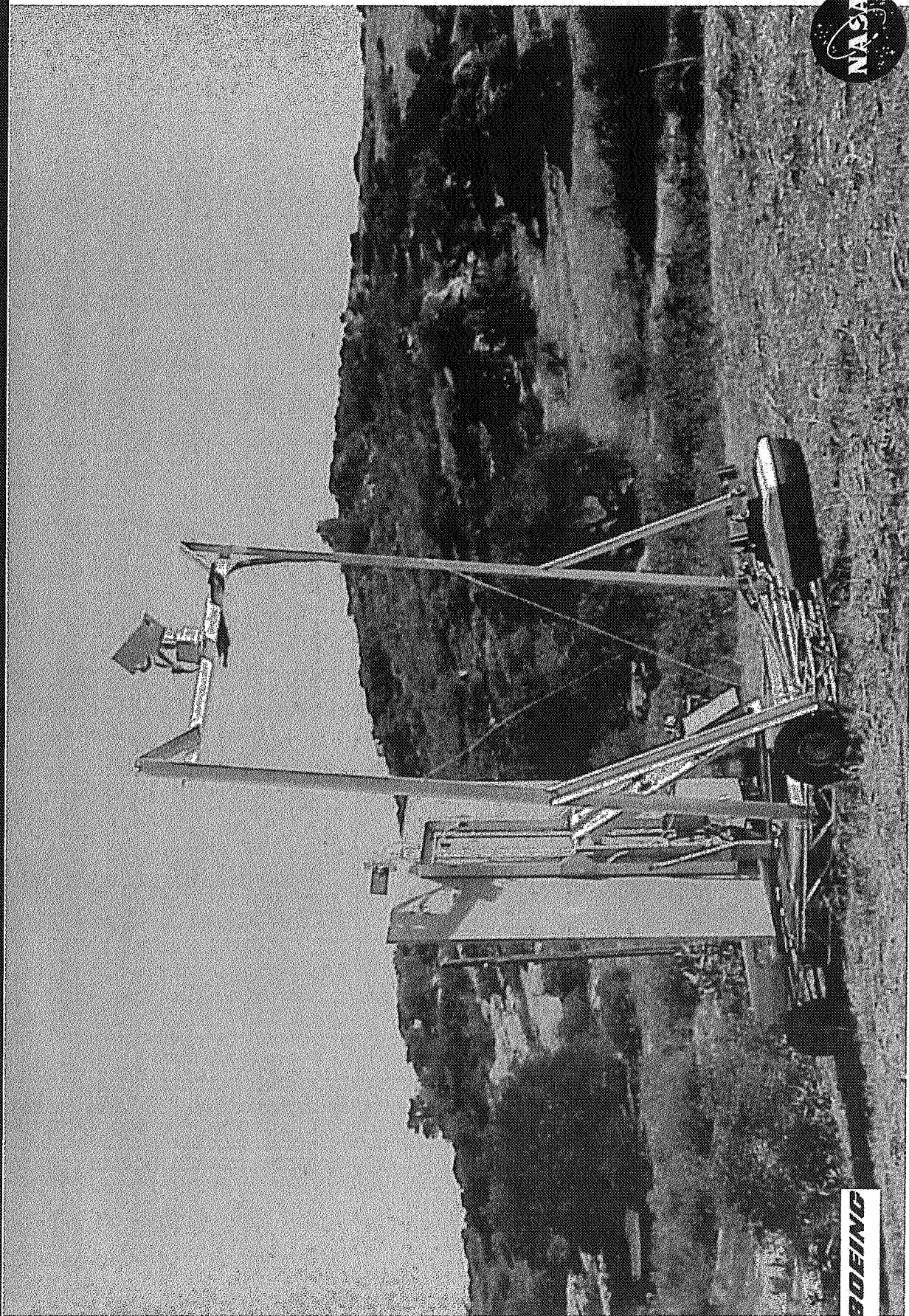


WPT from Lunar Mountaintop  
(spherical Moon, vertical scale exaggerated)

# Laser Range from Example Mountain-Top (Direct Line-of-Sight from Point E)



# Rover for Demonstration of Wireless Power Transmission Technology



## Key Points and Conclusions (1 of 3)

- SSP technology can enable space exploration and development in the near term
  - Power Plug can be deployed from existing launch vehicles
  - Mars Clipper and Propellant Depot can bridge the gap between Power Plug and commercial SSP
  - Near-term applications provide top-level traceability to commercial SSP
- Photovoltaic microwave SSP systems are efficient, easily assembled, and can beam power through clouds and light rain
  - Microwave WPT technology is relatively mature
  - Need specialized ground asset: rectenna
  - Cost to first power (minimum system size) is large
- Laser SSP systems allow smooth transition from conventional power to SSP
  - Small aperture size allows for low cost to first power
  - System upgrades and degrades gracefully
  - Can use independently beneficial ground asset: terrestrial PV arrays, which may already be in place

## Key Points and Conclusions (2 of 3)

- Laser SSP systems open up new architecture options
  - Lower efficiencies of current and near-term technology would seem to necessitate higher satellite masses than microwave systems; however, specific power may be competitive because
    - > Small apertures may minimize WPT system mass
    - > Lasers can be distributed, minimizing power management & distribution mass
  - Narrow beams can overlap to generate a “top hat” energy profile
    - > Allows for better use of land at receiver site
  - Lower land use requirement facilitates multiple receiver sites to mitigate weather outages
  - Shape of energy distribution can be tailored to available ground site
  - Gravity gradient-stabilized Sun Tower-like architectures may make more sense for lasers than for microwave systems
    - > Cosine loss at midday may be mitigated by ambient sunlight at receiver site
    - > Use of rotating arrays and long tether may not mitigate cosine loss sufficiently to justify additional weight and complexity; rigid arrays with both sides able to convert sunlight to electricity may be preferable

## Key Points and Conclusions (3 of 3)

- Laser and microwave SSP systems may have differing design drivers
  - Microwaves require large transmit/receive apertures, so WPT is major design driver
  - Laser performance is temperature-dependent, so thermal management may be major design driver
- Cryogenic propellant depots can enable the development of large-scale (but sub-SPS) space power systems and support the exploration and development of space
- Beam-powered lunar rover technology can pave the way to SPS, while prospecting for resources at the lunar poles